[Sports Physical Therapy] CEU

Changes in Landing Mechanics in Patients Following Anterior Cruciate Ligament Reconstruction When Wearing an Extension Constraint Knee Brace

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Background: Anterior cruciate ligament (ACL) reconstruction is associated with a high incidence of second tears (graft tears and contralateral ACL tears). These secondary tears have been attributed to asymmetrical lower extremity mechanics. Knee bracing is one potential intervention that can be used during rehabilitation that has the potential to normalize lower extremity asymmetry; however, little is known about the effect of bracing on movement asymmetry in patients following ACL reconstruction.

Hypothesis: Wearing a knee brace would increase knee joint flexion and joint symmetry. It was also expected that the joint mechanics would become more symmetrical in the braced condition.

Objective: To examine how knee bracing affects knee joint function and symmetry over the course of rehabilitation in patients 6 months following ACL reconstruction.

Study Design: Controlled laboratory study.

Level of Evidence: Level 3.

Methods: Twenty-three adolescent patients rehabilitating from ACL reconstruction surgery were recruited for the study. The subjects all underwent a motion analysis assessment during a stop-jump activity with and without a functional knee brace on the surgical side that resisted extension for 6 months following the ACL reconstruction surgery. Statistical analysis utilized a 2 × 2 (limb × brace) analysis of variance with a significant alpha level of 0.05.

Results: Subjects had increased knee flexion on the surgical side when they were braced. The brace condition increased knee flexion velocity, decreased the initial knee flexion angle, and increased the ground reaction force and knee extension moment on both limbs. Side-to-side asymmetry was present across conditions for the vertical ground reaction force and knee extension moment.

Conclusion: Wearing a knee brace appears to increase lower extremity compliance and promotes normalized loading on the surgical side.

Clinical Relevance: Knee extension constraint bracing in postoperative ACL patients may improve symmetry of lower extremity mechanics, which is potentially beneficial in progressing rehabilitation and reducing the incidence of second ACL tears.

Keywords: knee injury; biomechanics; function; jump

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Anterior cruciate ligament (ACL) reconstructions are one of the most common lower extremity surgical procedures associated with sports injury.[12,17,30] ACL injuries often require extensive rehabilitation following surgery to return individuals to their prior level of function.[15] During rehabilitation, an outcome goal is to normalize the function of the surgical side.[5,21] Unfortunately, current research suggests that patients undergoing rehabilitation continue to exhibit asymmetrical lower extremity function, which is associated with high second tear rates (second ipsilateral or first contralateral).[11,20,21,25,27] The rate of a second ACL injury is twice as high in adolescents, which increases the potential for long-term disability because of an increase in the incidence of knee osteoarthritis 10 to 12 years following surgery as a result of the injury.[31] To optimize patient function following ACL reconstruction, it is imperative that we understand how both surgery and rehabilitation affect lower extremity function.

The aim of knee bracing is to improve joint function and protect the joint from injury while the graft is healing.[18,26] Previous research has suggested that functional knee braces may alter knee joint mechanics during jump landings.[16,35,36] The ACL is under greatest tension when the knee is in extension,[32] which prompted the development of a knee brace that resists knee joint extension. Research has suggested that individuals wearing the brace exhibit increases in knee flexion at initial contact and decreases in peak knee flexion during a jump landing.[16,36] Studies of knee braces without an extension constraint mechanism suggest that braces decrease peak knee flexion in healthy subjects. No data were reported on knee flexion at initial contact when the ACL is under the greatest loads.[32,35] However, the effect of a functional knee brace with an extension constraint mechanism has not been previously studied in ACL patients during a jumping task. Since it is well established that patients following ACL reconstruction move differently than controls, it is important to examine specifically how individuals function with bracing.[13,33,34] Bilateral symmetry is a desired functional standard during rehabilitation.[5,25,27] These characteristics are often utilized for discharge criteria as it relates to range of motion, strength, and function.[2,3]

Thus, the purpose of this study was to examine the effects of a functional knee brace that resisted terminal extension on knee mechanics and bilateral symmetry during a stop-jump landing in patients 6 months following ACL reconstruction. It was hypothesized that wearing the brace would increase knee joint flexion and joint symmetry. It was also expected that the joint mechanics would become more symmetrical in the braced condition.

METHODS

Subjects

All subjects signed an informed consent form that had been approved by the Medical Center's Institutional Review Board prior to study initiation. Fourteen female and 9 male adolescent patients (mean age, 16.2 ± 1.2 years; mean height, 1.7 ± 0.1 m; mean mass, 72.2 ± 15.6 kg; time following ACL reconstruction, 6.2 ± 0.6 months) participated in the study at approximately 6 months following ACL reconstruction surgery. All subjects received an ACL tibial tunnel–independent reconstruction with a hamstring graft.[1] Fifteen of 23 patients had a concomitant meniscus repair or meniscectomy. Patients were excluded from this study if they had a previous ACL reconstruction surgery or any history of other lower extremity surgeries. All subjects were high school or collegiate athletes who were expected to return to cutting and jumping sports following surgery. Following surgery, all subjects completed a traditional rehabilitation program under the direction of a licensed physical therapist in their local community.

Data Collection Procedure

The warm-up protocol and marker placement used in this study have been previously reported.[9] Subjects had 46 retroreflective markers placed on various lower extremity landmarks to track segmental motion during testing (Figures 1a and 1b). Three-dimensional coordinate data were collected using an 8-camera motion capture system at a sampling rate of 120 Hz (Motion Analysis Corporation, Santa Rosa, California), while the ground reaction forces were collected using 2 force plates that were embedded in the walkway and were sampling at 2400 Hz (AMTI, Watertown, Massachusetts). During testing, subjects performed 5 vertical stop-jump tasks with and without the functional knee brace on the surgical limb (DonJoy Orthopaedics LLC, Vista, California).[9] Prior to testing, all patients had been released by the treating surgeon for sports participation including and not limited to running, cutting, and jumping. All subjects were instructed to use the brace during recreational activities for a minimum of 4 weeks prior to testing. During the vertical stop-jump task, subjects ran straight forward taking off on 1 foot, landing on 2 feet, and taking off again on 2 feet.[8] The approach run was up to 5 steps but the distance of approach was not restricted. Subjects were instructed to approach as fast as they could and jump as high as they could safely, with no instructions on how to land or what to do with their arms. Subjects practiced the task between 3 and 5 times until they were comfortable with the movement. The nonbraced condition was tested first, followed by the braced condition. Subjects were allowed adequate rest between trials and between conditions to minimize the effects of fatigue.

Data Reduction and Analysis

The coordinate data were filtered using a low-pass Butterworth filter at 12 Hz. The ground reaction force data were filtered using a low-pass Butterworth filter at 100 Hz. Time series data for the kinematics and kinetics variables were calculated using Visual 3D software (C-Motion, Bethesda, Maryland). Joint angles were calculated as Cardan angles between adjacent local segments, and joint moments were calculated through an inverse dynamic approach and transferred into the local segment coordinate system and were expressed as internal moments. Ground reaction forces were normalized to body weight. Joint moments were normalized to body weight and height. All data were analyzed from the first point of contact on

Figure 1. Marker set utilized during the data collection.

the force plates, the initial land phase, until the subject left the plate again at takeoff.

Because of the importance of sagittal plane biomechanics in determining ACL loading, sagittal plane variables at specific events were extracted for analysis.[32] Knee flexion and knee flexion velocity were examined at initial contact and peak during the landing phase. The knee flexion angle was also examined at the time of the peak knee flexion velocity. The peak vertical ground reaction force (VGRF) was examined during the weight acceptance and propulsion phases of the jump.[23] Finally, the peak knee extension moment and the knee extension moment at peak knee flexion velocity were calculated. Because peak knee flexion was chosen as an evaluation variable, published data present evidence[6] that peak knee flexion velocity and ACL injuries typically occur within the first 20% of the landing stance phase. The linear speed of the sacral marker from the 1-footed takeoff to the 2-footed landing was used to quantify approaching speed. Jump height was calculated by subtracting the vertical coordinate of the sacral marker during the static trial from the maximum vertical coordinate of the sacral marker during jump trials. The extractions of the dependent variables from the time series output were performed using subroutines developed in Matlab R2010a (MathWorks Inc, Natick, Massachusetts).

The approach speed and jump height were compared between the nonbraced and braced conditions using paired *t* tests. The kinematic and kinetic variables of interest were compared between the braced and nonbraced conditions and between the surgical and nonsurgical limbs using a series of repeated-measures analyses of variance (brace × limb). Tukey post hoc testing was conducted to evaluate the simple main effect if a significant interaction was found. Type I error was established at 0.05 for significance. Statistical analyses were completed in SPSS 12.0.1 (SPSS Inc, Chicago, Illinois).

RESULTS

No significant differences were observed in jump height between the nonbraced and braced conditions (nonbraced, 0.37 ± 0.10 m; braced, 0.36 ± 0.10 m; $P = 0.14$). However,

Table 1. Means ± standard deviations of dependent variables for the braced (B) and nonbraced (NB) condition on the surgical (S) and nonsurgical (NS) limbs and the associated *P* values of the statistical tests

					P Values[a]		
Variables	**S-NB**	**NS-NB**	**S-B**	**NS-B**	**Brace ME**	**Limb ME**	**Int**
Initial knee flexion velocity, deg/s	158.4 ± 174.0	150.8 ± 143.1	196.0 ± 167.6	181.0 ± 133.3	**0.02**	0.74	0.63
Peak knee flexion velocity, deg/s	701.0 ± 101.2	731.8 ± 108.4	733.5 ± 124.7	791.1 ± 116.6	**<0.01**	0.05	0.16
Initial knee flexion angle, deg	19.8 ± 7.1	19.0 ± 8.2	18.3 ± 7.0	16.6 ± 7.1	**0.01**	0.46	0.59
Knee flexion angle at peak flexion velocity, deg	39.0 ± 5.7	39.0 ± 6.7	38.4 ± 6.1	38.3 ± 5.9	0.22	0.94	0.99
Peak knee flexion angle, deg	72.3 ± 8.0	73.2 ± 8.3	75.0 ± 9.4	73.8 ± 9.7	0.06	0.91	**0.01**
Peak impact VGRF, BW	1.6 ± 0.5	2.0 ± 0.6	1.8 ± 0.5	2.2 ± 0.6	**<0.01**	**<0.01**	0.98
Peak propulsion VGRF, BW	1.2 ± 0.2	1.4 ± 0.2	1.3 ± 0.2	1.4 ± 0.2	0.51	**<0.01**	0.79
Knee extension moment at peak knee flexion velocity, BW*BH	0.04 ± 0.03	0.07 ± 0.03	0.05 ± 0.03	0.08 ± 0.03	**<0.01**	**<0.01**	0.70
Peak knee extension moment, BW*BH	0.10 ± 0.03	0.14 ± 0.03	0.11 ± 0.03	0.15 ± 0.03	**0.03**	**<0.01**	0.30

ME, main effect; Int, interaction (all reported in *P* values); VGRF, vertical ground reaction force; BW, body weight; BH, body height.
[a]Boldfaced values indicate statistical significance.

subjects had a faster approach speed during the braced condition when compared with the nonbraced condition (nonbraced, 2.16 ± 0.50 m/s; braced, 2.32 ± 0.51 m/s; $P < 0.01$).

With regard to the kinematics (Table 1, Figures 2 and 3), a significant interaction was found for the peak knee flexion angle. Post hoc testing indicated that the brace condition increased the peak knee flexion angle only on the surgical limb. The main effects for the braced condition were an increased initial knee flexion velocity ($P < 0.02$) and peak knee flexion velocity ($P < 0.01$) but decreased the initial knee flexion angle ($P < 0.01$). No main effects for limb were observed.

With regard to the kinetics (Table 1, Figures 4 and 5), the braced condition significantly increased the ground reaction force by 10% during the early stance phase and increased the knee extension moments during the early and middle portions of the stance phase. The surgical knee demonstrated a statistically significant decrease in the vertical ground reaction force and a decrease in the knee extension moment during the entire stance phase when compared with the nonsurgical knee. No interaction was observed for the kinetic variables. The main effects for the brace condition showed that when wearing the brace, there was a statistically significant increase in the peak impact VGRF, knee extension moment at peak knee flexion velocity, and the peak knee extension moment (Table 1). A statistically significant decrease in the peak impact VGRF, peak propulsion VGRF, knee extension moment at peak knee flexion velocity, and peak knee extension moment was recorded for the surgical limb when compared with the nonsurgical limb (Table 1).

DISCUSSION

The use of a functional knee brace to normalize movement following ACL reconstruction has been debated.[15,18] Current

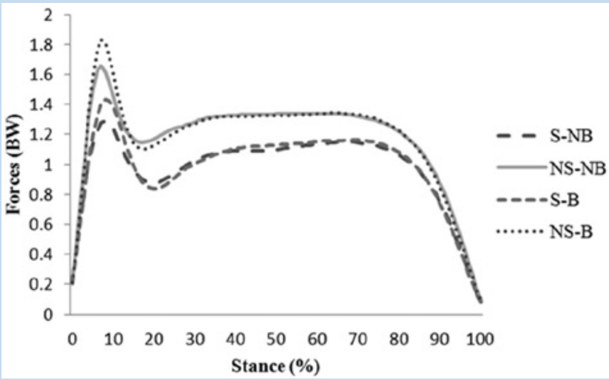

Figure 2. Knee flexion angle trajectories during the landing phase of the stop jump for the surgical (S) and nonsurgical (NS) limbs in the braced (B) and nonbraced (NB) conditions. BW, body weight.

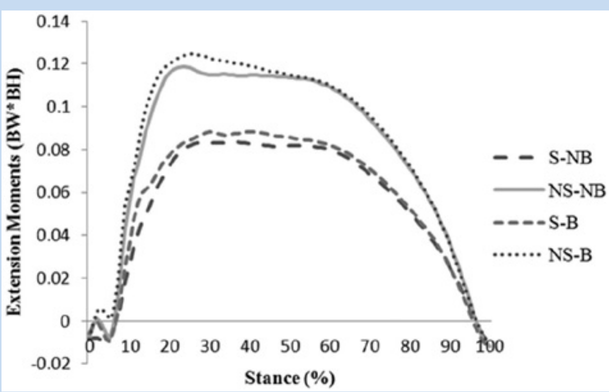

Figure 3. Knee flexion velocity trajectories during the landing phase of the stop jump for the surgical (S) and nonsurgical (NS) limbs in the braced (B) and nonbraced (NB) conditions. BW, body weight; BH, body height.

research suggests that patients following ACL reconstruction exhibit functional asymmetries up to 2 years following the surgery.[14,16,19,20,23,35] In these studies, the surgical knee has decreased function and moves through a decreased range of motion during eccentric loading.[2,13,18] Recently, the asymmetry in knee kinetics was associated with an elevated risk of sustaining a second ACL tear.[35] The current study suggests that ACL reconstruction patients alter their landing kinematics and kinetics when wearing a knee brace that resists terminal extension (Figures 2-5).

The brace increased knee flexion on the surgical side to a greater degree than the nonsurgical side; the nonsurgical side exhibited no change between the conditions tested. This supports our initial hypothesis in which we expected an increase in knee flexion when using the brace. However, this is contradictory to previous reports in healthy subjects.[6,8,16] The differences are likely because of the differences in the subject population (ACL

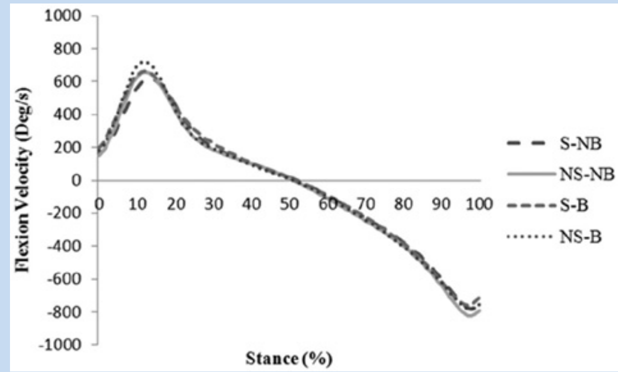

Figure 4. Vertical ground reaction forces during the landing phase of the stop jump for the surgical (S) and nonsurgical (NS) limbs in the braced (B) and nonbraced (NB) conditions.

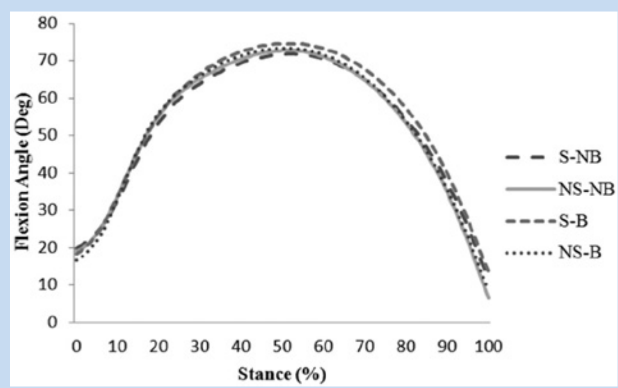

Figure 5. Knee extension moment trajectories during the landing phase of the stop jump for the surgical (S) and nonsurgical (NS) limbs in the braced (B) and nonbraced (NB) conditions.

reconstruction vs healthy controls), brace condition, as well as the amount of time that the subjects were allowed to acclimate to the brace.[10,26,27] As a result, ACL patients were more likely accommodated to the brace condition and responded differently than an individual wearing the brace for the first time.[29]

During the brace condition, there was an increase in the knee flexion velocities for both limbs; however, there was a decrease in the knee flexion angle at initial contact for both limbs. The flexion velocity findings were expected and desirable since these results suggest that the brace was promoting an earlier reduction in tension on the ACL, based on previous work, with the increasing rate of flexion on landing.[32] On the contrary, reduced knee flexion at initial contact in the brace condition was contrary to our hypothesis and based on bracing literature in healthy controls. Previous work using the same brace observed the opposite finding where the brace promoted increased knee flexion at initial contact.[36] Interestingly, the average peak knee flexion is approximately 10° greater in the healthy controls in the prior study.[36] This observation supports previous research suggesting fundamental differences between the ACL reconstructed and control subjects.[1,10,13,27]

The brace altered whole body and local kinetic values during the stop-jump landing (Figures 4 and 5). During the brace condition, the increased vertical ground reaction force and knee extension moment was unexpected but correlates with the increased approach speed in the brace condition. The brace may have increased confidence to accelerate and decelerate faster, which could result in an increase in the vertical ground reaction force and the resultant knee joint moments.

Across both of the brace test conditions there was a consistent difference in the total body and local knee joint kinetics (Table 1, Figures 4 and 5). The peak vertical ground reaction force and the peak knee extension moments were elevated on the ACL side, consistent with prior research.[7,14,22,24,27] Kinetic asymmetries in the lower extremity may elevate the risk for a second ACL rupture.[1]

There are several limitations to the study, including unknown compliance in brace use. The patients' compliance and knee joint loading while wearing the brace likely affect each individual's landing mechanics. Another limitation is that the testing order was not randomized. This limitation would have a larger implication if fatigue occurred. However, the 16 to 20 stop-jump trials produced minimal exertion. In addition, the adolescent population and small sample size limits the external validity.[31] Finally, this study is limited because of the surface-based motion capture protocol as opposed to bone pins for the tracking of segmental motion during the trials. Previous research studies have shown the error provided by surface-based methodology.[4,28]

CONCLUSION

The current study suggests that wearing this knee brace promotes increased knee flexion and knee flexion velocity during these maneuvers. However, large bilateral asymmetries still remain 6 months following surgery, which may be associated with the risk for a contralateral ACL tear.

REFERENCES

1. Abebe ES, Moorman CT 3rd, Dziedzic TS, et al. Femoral tunnel placement during anterior cruciate ligament reconstruction: an in vivo imaging analysis comparing transtibial and 2-incision tibial tunnel-independent techniques. *Am J Sports Med.* 2009;37:1904-1911.
2. Barber-Westin SD, Noyes FR. Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. *Arthroscopy.* 2011;27:1697-1705.
3. Barber-Westin SD, Noyes FR. Objective criteria for return to athletics after anterior cruciate ligament reconstruction and subsequent reinjury rates: a systematic review. *Phys Sportsmed.* 2011;39:100-110.
4. Benoit DL, Ramsey DK, Lamontagne M, Xu L, Wretenberg P, Renström P. Effect of skin movement artifact on knee kinematics during gait and cutting motions measured in vivo. *Gait Posture.* 2006;24:152-164.
5. Biggs A, Jenkins WL, Urch SE, Shelbourne KD. Rehabilitation for patients following ACL reconstruction: a knee symmetry model. *North Am J Sports Phys Ther.* 2009;4:2-12.
6. Boden BP, Dean GS, Feagin JA Jr, Garrett WE Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics.* 2000;23:573-578.
7. Bush-Joseph CA, Hurwitz DE, Patel RR, et al. Dynamic function after anterior cruciate ligament reconstruction with autologous patellar tendon. *Am J Sports Med.* 2001;29:36-41.
8. Chappell JD, Yu B, Kirkendall DT, Garrett WE. A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *Am J Sports Med.* 2002;30:261-267.
9. Dai B, Butler RJ, Garrett WE, Queen RM. Anterior cruciate ligament reconstruction in adolescent patients: limb asymmetry and functional knee bracing. *Am J Sports Med.* 2012;40:2756-2763.
10. Daniel DM, Stone ML, Dobson BE, Fithian DC, Rossman DJ, Kaufman KR. Fate of the ACL-injured patient. A prospective outcome study. *Am J Sports Med.* 1994;22:632-644.
11. Dunn WR, Lyman S, Lincoln AE, Amoroso PJ, Wickiewicz T, Marx RG. The effect of anterior cruciate ligament reconstruction on the risk of knee reinjury. *Am J Sports Med.* 2004;32:1906-1914.
12. Gianotti SM, Marshall SW, Hume PA, Bunt L. Incidence of anterior cruciate ligament injury and other knee ligament injuries: a national population-based study. *J Sci Med Sport.* 2009;12:622-627.
13. Gokeler A, Hof AL, Arnold MP, Dijkstra PU, Postema K, Otten E. Abnormal landing strategies after ACL reconstruction. *Scand J Med Sci Sports.* 2010;20:e12-e19.
14. Herrington L, Hatcher J, Hatcher A, McNicholas M. A comparison of Star Excursion Balance Test reach distances between ACL deficient patients and asymptomatic controls. *Knee.* 2009;16:149-152.
15. Kvist J. Rehabilitation following anterior cruciate ligament injury: current recommendations for sports participation. *Sports Med.* 2004;34:269-280.
16. Lin CF, Liu H, Garrett WE, Yu B. Effects of a knee extension constraint brace on selected lower extremity motion patterns during a stop-jump task. *J Appl Biomech.* 2008;24:158-165.
17. Mihata LC, Beutler AI, Boden BP. Comparing the incidence of anterior cruciate ligament injury in collegiate lacrosse, soccer, and basketball players: implications for anterior cruciate ligament mechanism and prevention. *Am J Sports Med.* 2006;34:899-904.
18. Moller E, Forssblad M, Hansson L, Wange P, Weidenhielm L. Bracing versus nonbracing in rehabilitation after anterior cruciate ligament reconstruction: a randomized prospective study with 2-year follow-up. *Knee Surg Sports Traumatol Arthrosc.* 2001;9:102-108.
19. Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after anterior cruciate ligament reconstruction: criteria-based progression through the return-to-sport phase. *J Orthop Sports Phys Ther.* 2006;36:385-402.
20. Myer GD, Schmitt LC, Brent JL, et al. Utilization of modified NFL combine testing to identify functional deficits in athletes following ACL reconstruction. *J Orthop Sports Phys Ther.* 2011;41:377-387.
21. Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. *Am J Sports Med.* 1991;19:513-518.
22. Orishimo KF, Kremenic IJ, Mullaney MJ, McHugh MP, Nicholas SJ. Adaptations in single-leg hop biomechanics following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2010;18:1587-1593.
23. Paterno MV, Ford KR, Myer GD, Heyl R, Hewett TE. Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. *Clin J Sport Med.* 2007;17:258-262.
24. Paterno MV, Schmitt LC, Ford KR, Rauh MJ, Myer GD, Hewett TE. Effects of sex on compensatory landing strategies upon return to sport after anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther.* 2011;41:553-559.
25. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med.* 2010;38:1968-1978.
26. Pezzullo DJ, Fadale P. Current controversies in rehabilitation after anterior cruciate ligament reconstruction. *Sports Med Arthrosc.* 2010;18:43-47.
27. Reid A, Birmingham TB, Stratford PW, Alcock GK, Giffin JR. Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. *Phys Ther.* 2007;87:337-349.
28. Reinschmidt C, van den Bogert AJ, Nigg BM, Lundberg A, Murphy N. Effect of skin movement on the analysis of skeletal knee joint motion during running. *J Biomech.* 1997;30:729-732.

29. Rishiraj N, Taunton JE, Lloyd-Smith R, Regan W, Niven B, Woollard R. Functional knee brace use effect on peak vertical ground reaction forces during drop jump landing. *Knee Surg Sports Traumatol Arthrosc*. 2012;20:2405-2412.
30. Salmon L, Russell V, Musgrove T, Pinczewski L, Refshauge K. Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction. *Arthroscopy*. 2005;21:948-957.
31. Shelbourne KD, Gray T, Haro M. Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. *Am J Sports Med*. 2009;37:246-251.
32. Taylor K, Terry M, Utturkar G, et al. The measurement of in vivo ACL strain during dynamic jump landing. *J Biomech*. 2011;44:365-371.
33. von Porat A, Henriksson M, Holmström E, Roos EM. Knee kinematics and kinetics in former soccer players with a 16-year-old ACL injury—the effects of twelve weeks of knee-specific training. *BMC Musculoskelet Disord*. 2007;8:35.
34. Yamazaki J, Muneta T, Ju YJ, Sekiya I. Differences in kinematics of single leg squatting between anterior cruciate ligament-injured patients and healthy controls. *Knee Surg Sports Traumatol Arthrosc*. 2010;18:56-63.
35. Yeow CH, Gan WL, Lee PV, Goh JC. Effect of an anterior-sloped brace joint on anterior tibial translation and axial tibial rotation: a motion analysis study. *Clin Biomech (Bristol, Avon)*. 2010;25:1025-1030.
36. Yu B, Herman D, Preston J, Lu W, Kirkendall DT, Garrett WE. Immediate effects of a knee brace with a constraint to knee extension on knee kinematics and ground reaction forces in a stop-jump task. *Am J Sports Med*. 2004;32:1136-1143.